



The role of palaeogeography in the Phanerozoic history of atmospheric CO₂ and climate



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ABSTRACT

The role of the palaeogeography on the geological evolution of the global carbon cycle has been suspected since the development of the first global geochemical models in the early 80s. The palaeogeography has been rapidly recognized as a key factor controlling the long-term evolution of the atmospheric CO₂ through its capability of modulating the efficiency of the silicate weathering. First the role of the latitudinal position of the continents has been emphasized: an averaged low latitudinal position promotes the CO₂ consumption by silicate weathering, and is theoretically associated to low CO₂ periods. With the increase of model complexity and the explicit consideration of the hydrological cycle, the importance of the continentality factor has been recognized: periods of supercontinent assembly coincide with high pCO₂ values due to the development of arid conditions which weaken the silicate weathering efficiency. These fundamental feedbacks between climate, carbon cycle and tectonic have been discovered by pioneer modelling studies and opened new views in the understanding of the history of Earth's climate. Today, some of the key features of the Phanerozoic climate can be explained by: (1) continental drift; (2) small continental blocks moving to tropical belts; and (3) modulation of the climate sensitivity to CO₂ by palaeogeography changes. Those results emphasize the need for a careful process-based modelling of the water cycle and climate response to the continental drift.

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1. Introduction

Palaeogeography and Earth climate are tightly linked. As noticed by Hay et al. (1990), the existence of a link between the latitudinal

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distribution of land mass and the continental climate has been first postulated by [Lyell \(1830\)](#), almost a century before the publication of the continental drift theory ([Wegener, 1912](#)). Assuming a constant land surface, [Lyell \(1830\)](#) proposes that filling the Arctic region with emerged continents at the expense of equatorial territories would result in a severe polar glaciation and in a drop of the global temperature. Then comes the continental drift theory ([Wegener, 1912](#)) and the prediction of [K  ppen and Wegener \(1924\)](#) that if all continents are located in the equatorial area for a given past period, continental and shelfal markers of climate will all indicate warm conditions, making a strong case for a link between palaeogeography and climate.

Since the end of the seventies, an abundant literature deals with the link between continental configuration and climate. Land mass distribution modifies the regional and global climate ([Gyllenhaal et al., 1991](#)), through changes in the oceanic circulation ([Kennett, 1977](#); [von der Heydt and Dijkstra, 2006](#); [Lagabrielle et al., 2009](#) and reference therein; [Lefebvre et al., 2012](#); [Zhang et al., 2012](#)), albedo feedbacks ([Hay et al., 1990](#); [Horton et al., 2010](#)), and direct impact on the precipitation/evaporation balance ([Barron et al., 1989](#); [Otto-Bliesner, 1995](#)). In addition to geological features, climate modelling studies explore the role of the continental configuration on pCO_2 thresholds needed to explain ice/green-house successions ([Barron and Washington, 1982](#); [Crowley and Baum, 1991, 1995](#); [Barron et al., 1993](#); [Gibbs et al., 1997](#); [Hyde et al., 1999](#); [Herrmann et al., 2004](#); [Donnadieu et al., 2006](#); [Craggs et al., 2012](#); [Horton et al., 2012](#); [Spicer et al., 2008](#)). However all these studies share a common characteristic: they prescribe atmospheric greenhouse gas levels. Specifically, CO_2 level is a boundary condition and is thus assumed to be an external forcing of the climate system, whatever the continental configuration.

But things are more complex. Since weathering of Ca–Mg silicates of crustal rocks consumes atmospheric CO_2 at a rate depending on the Earth's climate, CO_2 levels are necessarily depending on the palaeogeography at long-term scale. Basically, the rock mineral dissolution directly depends: (1) on the availability of water, thus on the continental area located within humid climatic belts; and (2) on the temperature, thus on the latitudinal distribution of the continents. Surprisingly, the interplay between palaeogeography and global carbon cycle has not been often studied in the recent years, despite the fact that it may be potentially a first order forcing of climate at the geological timescale. Instead of working on the geography effect, most of the efforts have been concentrated on the role of land plants ([Berner, 2004](#)), and of mountain building and physical erosion ([Raymo et al., 1988](#); [Raymo, 1991](#)).

In this contribution, we propose an overview of the studies devoted to the impact of palaeogeography on the long-term carbon cycle ($>10^5$ yrs). We show that continental precipitations and runoff are highly sensitive to the palaeogeography. We demonstrate that the continental configuration is a first order factor controlling the atmospheric CO_2 level and the Earth's climate evolution.

2. Pioneer modelling studies of the impact of palaeogeography on the global carbon cycle

According to the Earth thermostat theory ([Walker et al., 1981](#)), for a given solid Earth CO_2 degassing, the total CO_2 consumption by continental weathering should be the same, whatever the location of continents. This is a direct consequence of the short response time of carbon and alkalinity in the ocean–atmosphere system, respectively 200 and 3 kyr ([Fran  ois and Godd  ris, 1998](#)) and of the negative feedback exerted by climate on weathering ([Walker et al., 1981](#)). The CO_2 consumption by silicate weathering is always tracking the CO_2 supply by solid Earth degassing, to avoid too large CO_2 fluctuations and repeated climatic catastrophes ([Berner and Caldeira, 1997](#)).

[Marshall et al. \(1988\)](#) first proposed that the palaeogeography might be a key parameter of the evolution of the geological carbon cycle ([Table 1](#)). They found that atmospheric CO_2 must be at high levels

when most of the continents are located around the poles. Conversely, CO_2 must be low and global climate cold when continents are located around the equator. They argue that this is a direct consequence of a promoted CO_2 consumption by continental silicate rock dissolution when continents are located in the warm equatorial belt. Because temperatures are higher at the equator than at the pole, [Marshall et al. \(1988\)](#) note that the weatherability (i.e., the susceptibility to weathering) is higher when continents are close to the equator. As a consequence, the same total weathering flux will be reached at a much lower CO_2 level compared to a world where continents are located at the pole. Although their study was conceptual with generic continental configurations, [Marshall et al. \(1988\)](#) had already proposed that the late Precambrian glaciations might have been promoted by an equatorial location of the continents.

[Worsley and Kidder \(1991\)](#) further explore the [Marshall et al. \(1988\)](#) hypothesis through additional qualitative considerations. Similarly to Marshall et al., they suggest that a ring world (all continents located along the equator) should be characterized by lower atmospheric CO_2 (and hence colder global conditions) than a cap world (all continents around the poles). Provocatively, [Worsley and Kidder \(1991\)](#) even propose that the averaged latitude of the continents alone specify CO_2 levels.

Marshall and collaborators were the first to couple a process-based climate model with a mathematical description of the continental weathering. The climate model used was quite simple: an energy-balanced model (EBM). This model calculates the Earth surface temperature as a function of latitude accounting for the vertical budget of energy and for the meridional heat transport. Similar models, coupling a description of the carbon cycle with a zonal energy-balanced model, have been used to explore the Phanerozoic CO_2 history ([Fran  ois and Walker, 1992](#); [Godd  ris and Fran  ois, 1995](#); [Godd  ris and Joachimski, 2004](#); [Tajika, 2007](#)). However, it is important to note that if EBM models are reliable in terms of temperature predictions, they lack a physical description of the water cycle and, as such, are not able to calculate accurately the runoff, a key parameter of continental weathering ([Dessert et al., 2003](#); [Oliva et al., 2003](#)). To overcome this limitation, a new generation of models has been developed.

3. Exploring the role of palaeogeography on the water and carbon cycle

Continental silicate weathering and associated CO_2 sink are heavily dependent on continental runoff, which is the difference between rainfall and evapotranspiration. As such, the relationship between palaeogeographical setting and hydrological cycle must be understood, and this was beyond the abilities of the energy-balanced models previously used. The first study exploring the role of the continent distribution on the hydrologic cycle with an appropriate model was performed in 1989 by Barron and co-authors. They note that the water cycle is an essential part of the geochemical cycles (weathering, erosion, sedimentation), and that too much attention has been paid to temperature reconstructions at the expense of water cycle reconstructions. They explore the role of palaeogeography on the water cycle with the NCAR Community Climate Model (spatial resolution of 7.5° long $\times$ 4.5° lat). Contrary to energy-balanced models, the CCM includes a calculation of evaporation and condensation, and cloud cover. Such 3D climate models (also called General Circulation Models or GCM) explicitly simulate the water cycle, calculating the evaporation and rainfall on a 2-D map of the world, and the three-dimensional transport of water vapour in the atmosphere. Their main finding is that continental positions can strongly alter the hydrologic cycle (rainfall and runoff) if their positions affect the supply of moisture to the atmosphere. This is particularly the case in a simulation assuming a continuous belt of continents between 15° S and 15° N. Compared to the present day, this ring world is 8° C globally warmer, but global rainfall is maintained at its present day rate because the area of intense evaporation along the equator is lacking oceanic surfaces. Because of this intense continental evaporation, continental runoff

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